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Hyperfast pulsars as the remnants of massive stars ejected from young star clusters

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ABSTRACT
Recent proper motion and parallax measurements for the pulsar PSR B1508+55 gave the highest (transverse) velocity ($\sim 1\,100\,\mathrm{km\,s^{-1}}$) ever measured for a neutron star (Chatterjee et al. 2005). The spin-down characteristics of PSR B1508+55 (typical of *non-recycled* pulsars) imply that the high velocity of this pulsar cannot be solely due to disruption of a tight massive binary system. A possible way to account for the high velocity of PSR B1508+55 is to assume that at least a part of this velocity is due to a natal kick or a post-natal acceleration (Chatterjee et al. 2005). We propose an alternative explanation for the origin of hyperfast pulsars based on the idea that they could be the remnants of a *symmetric* supernova explosion of a high-velocity massive star (or its helium core) which attained its peculiar velocity (similar to that of the pulsar) in the course of a strong three or four body dynamical encounter in the core of the parent young massive star cluster. Our proposal implies that the dense cores of young massive star clusters (located either in the Galactic disk or near the Galactic centre) could also produce the so-called hypervelocity stars (Brown et al. 2005) – the ordinary stars moving with a speed of $\sim 1\,000\,\mathrm{km\,s^{-1}}$.

Key words: pulsars: general – pulsars: individual: B1508+55, B2224+65, B2011+38 – stars: black holes – stars: neutron: RX J0822-4300 – methods: N-body simulations – stellar dynamics.

1 INTRODUCTION

It has been known for a long time that the typical peculiar space velocities of pulsars are an order of magnitude larger that those of their progenitors – the massive stars (e.g. Gott, Gunn & Ostriker 1970). Subsequent proper motion measurements for pulsars suggested that some of them could be very fast objects, with peculiar speeds of up to $\sim 1\,000\,\mathrm{km\,s^{-1}}$ (e.g. Chatterjee & Cordes 2004; Hobbs et al. 2005). Two mechanisms have been proposed for the origin of high-velocity pulsars. The first one involves the disruption of tight massive binary systems following (symmetric) supernova explosion (e.g. Iben & Tutukov 1996). The second one is based on a natal kick (e.g. Shklovskii 1970; Dewey & Cordes 1987) or a post-natal acceleration (e.g. Tademaru & Harrison 1975; Chugai 1984). The highest-velocity pulsars formed by the first mechanism are the remnants of the first supernova explosion and their peculiar velocities are due to the disintegration of very tight (semi-detached) binary systems by the second supernova explosion. This mechanism, however, cannot produce velocities in excess of $\sim 1\,000\,\mathrm{km\,s^{-1}}$ (Portegies Zwart & van den Heuvel 1999). Moreover, the high-velocity pulsars formed in this way should be *recycled*, i.e. their spin characteristics should be significantly affected by the stellar wind of the companion star – the progenitor of the second supernova (cf. Chatterjee et al. 2005). The second mechanism relies on the asymmetry of the supernova explosion or on the asymmetric (electromagnetic or neutrino) emission from the new-born pulsar. In principle, this mechanism can produce solitary high-velocity pulsars with ordinary spin-down characteristics, i.e. non-recycled pulsars (e.g. Scheck et al. 2006). Thus, detection of non-recycled pulsars moving with a velocity $\geqslant 1\,000\,\mathrm{km\,s^{-1}}$ would suggest that the mechanism involving the binary disruption by the supernova explosion does not work at least in some cases. In the following we refer to pulsars (neutron stars) moving with velocities of $\gtrsim 1\,000\,\mathrm{km\,s^{-1}}$ as 'hyperfast pulsars' (a term introduced by Chatterjee et al. 2005).

Until recently the best candidates for hyperfast pulsars were PSR B2224+65 (associated with the well-known Guitar Nebula; Chatterjee & Cordes 2004) and PSR B2011+38

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(see Hobbs et al. 2005 and references therein), whose peculiar velocities (both $\sim 1\,500\,\mathrm{km\,s^{-1}}$) were inferred on the basis of proper motion measurements and dispersion measure distance estimates. The uncertainties associated with the distance estimates, however, leave a possibility that these velocities are overestimated. Recent proper motion and parallax measurements for the pulsar PSR B1508+55 gave the first example of a high velocity ($1\,083^{+103}_{-90}\,\mathrm{km\,s^{-1}}$) directly measured for a non-recycled pulsar (Chatterjee et al. 2005). This result proved the existence of a population of hyperfast neutron stars and implies that the peculiar velocity of PSR B1508+55 cannot be solely due to the disruption of a tight massive binary system. A possible way to account for the high velocity is to assume that at least a part of this velocity is due to a natal kick or a post-natal acceleration (Chatterjee et al. 2005).

In this paper, we propose an alternative explanation for the origin of hyperfast pulsars. We suggest that PSR B1508+55 (as well as other hyperfast neutron stars[1]) could be the remnant of a *symmetric* supernova explosion of a high-velocity massive star (or its helium core) which attained its peculiar velocity (similar to that of the pulsar) in the course of a strong three or four body dynamical encounter in the core of the parent young massive star cluster (YMSC).

Our suggestion is based on the recently recognized fact that massive ($\sim 10^5\,\mathrm{M}_\odot$) star clusters are still forming in the disk of the Milky Way (see Sect. 3) and on the hypothesis that the cores of YMSCs could harbour intermediate-mass black holes (IMBHs), i.e. black holes (BHs) with masses ranging from ~ 100 to $\sim 10^4\,\mathrm{M}_\odot$ (see Sect. 3). In Sect. 2 we briefly discuss the mechanisms for the origin of the so-called hypervelocity stars, the recently discovered class of stars moving with a speed of $\sim 1\,000\,\mathrm{km\,s^{-1}}$, and suggest that similar mechanisms (although acting in the different environment) could be responsible for the origin of hyperfast neutron stars. In Sect. 4 we estimate the maximum possible velocities of high-velocity escapers produced by various dynamical processes in the cores of YMSCs. In Sect. 5 we compare these estimates with results from numerical simulations while in Sect. 6 we discuss the ability of these processes to explain the origin of hyperfast pulsars and deal with some issues related to the content of the paper.

2 HYPERVELOCITY STARS AND MECHANISMS FOR THEIR PRODUCTION

The discovery of the first hyperfast pulsar (Chatterjee et al. 2005) coincides by time with the discovery of the hypervelocity stars[2] (e.g. Brown et al. 2005; Edelmann et al 2005; Hirsch et al. 2005). The existence of the latter was predicted by Hills (1988), who showed that a close encounter between the supermassive BH in the Galactic centre (e.g. Ghez et al. 2003; Schödel et al. 2003) and a tight binary system could be responsible for the ejection of one of the binary components with a velocity of up to several $1\,000\,\mathrm{km\,s^{-1}}$ (see also Hills 1991). Yu & Tremaine (2003) proposed two additional possible mechanisms for the production of hypervelocity stars. The first one involves close encounters between two single stars in the vicinity of a supermassive BH (the probability of this process, however, is very low and we will not discuss it further) while the second one is based on the interaction between a single star and a putative binary BH in the Galactic centre (e.g. Hansen & Milosavljević 2003).

The discovery of the hypervelocity stars (Brown et al. 2005; Edelmann et al. 2005; Hirsch et al. 2005; Brown et al. 2006) provides a support to the ejection mechanisms involving dynamical processes in the vicinity of the supermassive BH (Gualandris, Portegies Zwart & Sipior 2005; Baumgardt, Gualandris & Portegies Zwart 2006; Bromley et al. 2006), and now it is widely believed that these high-velocity objects originate in the Galactic centre (see, however, Edelmann et al. 2005; see also Sect. 6). It is, therefore, not impossible that some hyperfast pulsars (or their progenitor stars) were also ejected from the Galactic centre. For example, one of the hypervelocity stars is a early B-type star of mass $\sim 8\,\mathrm{M}_\odot$ (Edelmann et al. 2005), so that it is possible that it will end its life as a hyperfast pulsar. The proper motion measured for PSR B1508+55, however, indicates that this pulsar was born in the Galactic disk near the Cyg OB associations (Chatterjee et al. 2005; see also Sect. 6), i.e. its origin cannot be associated with the Galactic centre[3]. The proper motions of PSR B2224+65 and PSR B2011+38 also suggest that these pulsars were born far from the Galactic centre. Therefore one should look for other places in our Galaxy where one can find a sufficiently massive BH and where the number density of the local stellar population is high enough to ensure that close encounters between stars and the BH are frequent. Note that the characteristic age of the above-mentioned pulsars (ranging from ~ 0.4 to ~ 2.3 Myr) implies that at least these three pulsars were not ejected from the dense cores of globular clusters (whose typical age is $\gtrsim$ Gyr) and point to the more plausible cites of their origin – the YMSCs.

We note that with the YMSCs could be associated another important channel for production of high-velocity stars, namely through close dynamical encounters between stars in their cores. This process constitutes the base of the dynamical-ejection scenario proposed by Poveda, Ruiz & Allen (1967) to explain the origin of runaway OB stars. The most effective path for production of high-velocity stars by stellar encounters is through interaction between two hard binaries (e.g. Leonard & Duncan 1988, 1990). This process and processes involving dynamical encounters with IMBHs are discussed in detail in Sect. 4.

[1] Another example of a hyperfast neutron star was recently reported by Hui & Becker (2006) and Winkler & Petre (2006). Their proper motion measurements for the central compact object RX J0822-4300 in the supernova remnant (SNR) Puppis A suggest that the peculiar velocity of this neutron star could be as large as $\sim 1\,000 - 1\,500\,\mathrm{km\,s^{-1}}$, provided that the distance to these objects is ~ 2 kpc.

[2] In the following we use the term 'hypervelocity' [introduced by Hills (1988)] to designate the ordinary stars moving with a peculiar speed of $\gtrsim 1\,000\,\mathrm{km\,s^{-1}}$ while for neutron stars we reserve the term 'hyperfast' (see Sect. 1).

[3] For a nice picture illustrating the trajectory of the pulsar on the sky see `http://www.jb.man.ac.uk/news/fastestpulsar.html`

3 YOUNG MASSIVE STAR CLUSTERS

The recent discovery of young ($< 10^7$ yr) and massive ($> 10^4\,\mathrm{M}_\odot$) star clusters (e.g. Clark et al. 2005; Figer et al. 2006; cf. Knödlseder 2000; Alves & Homeier 2003) shows that these objects are quite numerous and that many YMSCs are still hidden from observers by the obscuring material in the Galactic plane (cf. Section 6). Assuming that the YMSCs are distributed uniformly throughout the Galaxy, one may expect that ~ 100 YMSCs of mass $\gtrsim 10^4 - 10^5\,\mathrm{M}_\odot$ currently exist in the disk of our Galaxy (e.g. Knödlseder et al. 2002; Hanson 2003; cf. Larsen 2006).

The dynamical evolution of YMSCs is dominated by massive stars, which rapidly sink to the cluster's centre on a time scale $t_{\rm cc} \sim 0.1 - 0.2\, t_{\rm rh}$, independent of cluster mass, size and density profile (e.g. Portegies Zwart & McMillan 2002; Gürkan, Freitag & Rasio 2004), where $t_{\rm rh}$ is the half-mass relaxation time scale given by (Spitzer 1987):

$$t_{\rm rh} \simeq \frac{0.14 M_{\rm cl}^{1/2} r_{\rm h}^{3/2}}{G^{1/2} \langle m \rangle \ln \Lambda}\,, \tag{1}$$

$M_{\rm cl}$ and $r_{\rm h}$ are the total mass and the characteristic (half-mass) radius of the cluster, G is the gravitational constant, $\langle m \rangle = M_{\rm cl}/N_{\rm cl}$ is the mean stellar mass, $N_{\rm cl}$ is the number of stars in the cluster, and $\ln \Lambda \simeq 10$ is the Coulomb logarithm. For $t_{\rm cc} = 0.15\, t_{\rm rh}$ and using Eq. (1), one has

$$t_{\rm cc} \simeq 3 \times 10^6\,{\rm yr} \left(\frac{M_{\rm cl}}{10^4\,\mathrm{M}_\odot}\right)^{1/2} \left(\frac{r_{\rm h}}{1\,{\rm pc}}\right)^{3/2} \times \left(\frac{\langle m \rangle}{\mathrm{M}_\odot}\right)^{-1} \left(\frac{\ln \Lambda}{10}\right)^{-1}. \tag{2}$$

Mass segregation drives YMSCs to core collapse and thereby strongly enhances their central density, that results in runaway stellar collisions and mergers. A natural consequence of the runaway process is the formation of a very massive star (VMS) (Portegies Zwart & McMillan 2002; Gürkan et al. 2004), provided that core collapse is completed before the most massive stars in the cluster explode as supernovae, i.e. $t_{\rm cc} \lesssim 3 \times 10^6$ yr. On this time-scale essentially all massive ($> 20\,\mathrm{M}_\odot$) stars in YMSCs can reach the cluster's centre to participate in the runaway process. For $M_{\rm cl} = 10^4 - 10^5\,\mathrm{M}_\odot$ and assuming a $0.2 - 120\,\mathrm{M}_\odot$ Salpeter initial mass function (in this case $\langle m \rangle \simeq 0.7\,\mathrm{M}_\odot$ and $N_{\rm cl} \simeq 1.5 \times 10^4 - 10^5$), one has from Eq. (2) that the runaway process occurs in YMSCs with $r_{\rm h} \lesssim 0.3 - 0.8$ pc. Observations show that most stars form in dense embedded clusters and that a characteristic radius of these clusters is ~ 1 pc independently of their mass (e.g. Kroupa & Boily 2002 and references therein). Thus, it is likely that the cores of the majority of YMSCs evolve through the collisional stage. Moreover, the origin of VMSs through the runaway mergers could take place already during the proto-cluster stage of evolution of YMSCs (i.e. on a time scale of $\lesssim 10^6$ yr), since the extended envelopes and accretion disks of pre-main-sequence stars strongly increase their collision cross sections (Soria 2006).

It is possible that the VMS formed through runaway collisions and mergers of ordinary massive stars will ultimately collapse to form an IMBH (e.g. Portegies Zwart & McMillan 2002). The mass of the IMBH formed in this way could be as large as $\sim 1\,000\,\mathrm{M}_\odot$ for $M_{\rm cl} \sim 10^5\,\mathrm{M}_\odot$ (Portegies Zwart et al. 2004). The stellar evolution calculations of Belkus, Van Bever & Vanbeveren (2007), however, indicate that the VMSs (with mass $\gtrsim 1\,000\,\mathrm{M}_\odot$) may end up as $\gtrsim 100\,\mathrm{M}_\odot$ BHs due to the significant mass loss in the form of stellar winds (see also Yungelson 2006).

Another possible formation scenario for IMBHs in the cores of YMSCs is the successive merging of several BHs of mass $\sim 50\,\mathrm{M}_\odot$ formed though mergers of massive binary stars (see Belczynski, Sadowski & Rasio 2004). This mechanism generates IMBHs with a mass $\gtrsim 10^2\,\mathrm{M}_\odot$.

It is also possible that IMBHs of mass $\sim 10^3 - 10^4\,\mathrm{M}_\odot$ are the descendants of old globular clusters disrupted by the tidal field of the Galactic disk or that they are formed from the core collapse of massive population III stars. Later they could be captured gravitationally by molecular clouds or by the already existing young star clusters. In the first case the IMBH initiates star formation in the cloud and, therefore, resides at the centre of the newly formed star cluster (Miller & Hamilton 2002), while in the second case the IMBH rapidly sinks to the center of the cluster due to the dynamical friction (Miller & Colbert 2004).

4 ORIGIN OF HYPERFAST PULSARS

We now consider the possibility that dynamical processes in the cores of YMSCs could be responsible for ejection of hypervelocity massive stars or their helium cores, whose subsequent collapse and (symmetric) supernova explosion result in the origin of hyperfast neutron stars (pulsars). In the following subsections we estimate the upper limits for the ejection speed produced by encounters involving: *i*) two hard binaries, *ii*) a hard binary and an IMBH, and *iii*) a single star and a hard binary IMBH.

4.1 Binary-binary encounters

In Sect. 2 we mentioned that the most effective path for production of high-velocity stars by stellar encounters is through interaction between two hard binaries, either the tidally captured ones or the primordial ones. Note that the tidal binaries are very hard by definition since the semi-major axes of their circularized orbits are at most a few stellar radii (e.g. Lee & Ostriker 1986; McMillan, McDermott & Taam 1987). Therefore it is likely that collisions involving tidal binaries play a dominant role in production of the fastest runaway stars. It is also important to note that due to the mass segregation the cores of YMSCs are over-represented by massive stars, so that most of tidally captured binaries should be the massive ones. Moreover, one can expect that almost all tidal binaries would be massive if the most massive stars are formed near the centres of their parent clusters (e.g. Bonnell, Bate & Zinnicker 1998; cf. Kroupa 2001).

Numerical simulations by Leonard & Duncan (1988, 1990) showed that the typical velocities at infinity (i.e. well after ejection) of runaway stars (produced in the course of binary-binary collisions) are similar to the orbital velocities of the binary components while the velocities of some escapers can be twice as large. Moreover, the maximum possible velocity attained by the lightest member of the binaries involved in the interaction (e.g. the helium core of a massive star or a early type B star) can be as large as the escape velocity from the surface of the most massive star in the binaries (Leonard 1991). For the upper main-sequence stars with the mass-radius relationship (Habets & Heintze 1981)

$$r_{\rm MS} = 0.8 \left(\frac{m_{\rm MS}}{\rm M_\odot}\right)^{0.7} {\rm R}_\odot \, , \qquad (3)$$

where $r_{\rm MS}$ and $m_{\rm MS}$ are the stellar radius and mass, the maximum possible velocity at infinity of ejected stars is a weak function of $m_{\rm MS}$, $V_{\infty,{\rm MS}}^{\rm max} \simeq 700\,{\rm km\,s^{-1}}(m_{\rm MS}/\,{\rm M_\odot})^{0.15}$ and could be as large as $\sim 1\,400\,{\rm km\,s^{-1}}$ (cf. Leonard 1991). The ejection velocity could be even larger if the binaries involved in the interaction are already evolved through a common-envelope phase and consist of two helium cores. In this case,

$$r_{\rm He} \simeq 0.2 \left(\frac{m_{\rm He}}{\rm M_\odot}\right)^{0.65} {\rm R}_\odot \, , \qquad (4)$$

where $r_{\rm He}$ and $m_{\rm He}$ are the radius and the mass of a helium core (Tauris & van den Heuvel 2006), so that $V_{\infty,{\rm He}}^{\rm max} \simeq 1\,400\,{\rm km\,s^{-1}}(m_{\rm He}/\,{\rm M_\odot})^{0.175} \sim 2\,300\,{\rm km\,s^{-1}}$.

Scattering experiments by Leonard (1991) showed that only a small fraction (less than one percent) of runaway stars released in the course of binary-binary collisions can attain the maximum possible velocity. So that, to produce at least one hypervelocity (massive) star during the first several million years of cluster evolution, the collisional time scale for binaries in the cluster core should be $\lesssim 10^4$ yr. The total rate of binary-binary encounters in the core of radius $r_{\rm c}$ is

$$\Gamma \sim \frac{1}{2} N_{\rm b} n_{\rm b} S_{\rm bb} V_{\rm rel} \, , \qquad (5)$$

where $N_{\rm b} \simeq (4\pi/3) r_{\rm c}^3 n_{\rm b}$, $n_{\rm b}$ is the number density of binaries, $V_{\rm rel}$ is the relative velocity of approach of the binaries at infinity,

$$S_{\rm bb} \sim \frac{2\pi G(m_1+m_2)a}{V_{\rm rel}^2} \qquad (6)$$

is the gravitationally focused cross section (Leonard 1989), and a is the binary semi-major axis. For the sake of simplicity we consider the equal-mass and equal-energy binaries and assume that one of the binary components is a 40 $\rm M_\odot$ main-sequence star while its companion is a He core of mass of 5 $\rm M_\odot$. From Eqs. (5) and (6), one has the mean time between binary-binary collisions (cf. Leonard 1989)

$$t_{\rm bb} \sim 8\times 10^3\,{\rm yr} \left(\frac{r_{\rm c}}{0.01\,{\rm pc}}\right)^{-3} \left(\frac{n_{\rm b}}{10^7\,{\rm pc^{-3}}}\right)^{-2} \times \left(\frac{V_{\rm rel}}{5\,{\rm km\,s^{-1}}}\right) \left(\frac{m_1}{40\,{\rm M_\odot}}\right)^{-1} \left(\frac{a}{50\,{\rm R_\odot}}\right)^{-1} . \qquad (7)$$

It follows from Eq. (7) that the collisional time scale is short enough (i.e. $\lesssim 10^4$ yr) if more than 10 massive binaries exist in the core of radius $\sim$ 0.01 pc. Assuming that almost all stars more massive than $\sim 20\,{\rm M_\odot}$ are segregated to the cluster core and exchanged in binaries, one has the minimum mass of the YMSC of $\sim 10^4\,{\rm M_\odot}$.

The recent discovery (Muno et al. 2006) of an anomalous X-ray pulsar in the $(4\pm 1)\times 10^6$ yr old massive ($\gtrsim 10^5\,{\rm M_\odot}$) Galactic star cluster Westerlund 1 (Clark et al. 2005) implies that the progenitor of this neutron star was a star with a zero-age main-sequence mass $\gtrsim 40\,{\rm M_\odot}$. Therefore, one can expect that the hypervelocity helium cores of massive stars ejected from the cores of YMSCs during the first several million years of cluster evolution will end their lives as hyperfast neutron stars (pulsars).

4.2 Exchange encounters between binary stars and an IMBH

Let us assume that the core of a YMSC harbours an IMBH of mass $M_{\rm BH} = 100 - 1\,000\,{\rm M_\odot}$, formed either through a runaway sequence of mergers or from the core collapse of a massive population III star (see Sect. 3).

A close encounter with the IMBH results in the tidal breakup of the binary, after which one of the binary components becomes bound to the IMBH while the second one (usually the least massive star) is ejected with a high speed, given by (Hills 1988; Yu & Tremaine 2003):

$$V_\infty \sim \left(\frac{GM_{\rm BH}}{r_{\rm t}}\right)^{1/4} \left[\frac{4Gm_1^2}{a(m_1+m_2)}\right]^{1/4} , \qquad (8)$$

where

$$r_{\rm t} \sim \left(\frac{M_{\rm BH}}{m_1+m_2}\right)^{1/3} a \qquad (9)$$

is the tidal radius and m_1 and m_2 are, respectively, the masses of the bound and ejected stars ($m_1 > m_2$). The fastest stars produced in this exchange process come from encounters involving the tightest binary systems (e.g. tidal binaries), since the tighter the binary the closer it can approach to the IMBH before tidal breakup. Combining Eqs. (8) and (9), one has

$$V_\infty \sim \left(\frac{M_{\rm BH}}{m_1+m_2}\right)^{1/6} \left(\frac{2Gm_1}{a}\right)^{1/2} . \qquad (10)$$

For a binary having a massive main-sequence component of mass $m_1 (\gg m_2)$ and $a \simeq 2.5 r_{1,{\rm MS}}$ (cf. Statler, Ostriker & Cohn 1987), one has from Eqs. (10) and (3)

$$V_\infty \sim 440\,{\rm km\,s^{-1}} \left(\frac{M_{\rm BH}}{\rm M_\odot}\right)^{1/6} \left(\frac{m_1}{\rm M_\odot}\right)^{-1/60} . \qquad (11)$$

For $M_{\rm BH} = 100 - 1\,000\,{\rm M_\odot}$ and $m_1 = 40 - 100\,{\rm M_\odot}$, one has from Eq. (11) that the low-mass binary component (e.g. the helium core of a massive star or a B star) can be ejected with a speed $V_\infty \sim 900 - 1\,300\,{\rm km\,s^{-1}}$. The ejection velocity could be somewhat higher if the binary involved in the encounter consists of two helium cores (cf. Sect. 4.1). For example, assuming that $m_{1,{\rm He}} = 10\,{\rm M_\odot}$ and $m_{2,{\rm He}} = 5\,{\rm M_\odot}$, and $a \simeq 5 - 10\,{\rm R_\odot}$, one has $v_\infty \simeq 850 - 1\,760\,{\rm km\,s^{-1}}$. Note that the weak dependence of V_∞ on $M_{\rm BH}$ implies that the hypervelocity helium cores can be produced by exchange encounters with stellar mass (i.e. $\sim 20\,{\rm M_\odot}$) BHs.

The mean collision time between binary stars and an IMBH is

$$t_{\rm coll} \sim 2\times 10^5\,{\rm yr} \left(\frac{n_{\rm b}}{10^7\,{\rm pc^{-3}}}\right)^{-1} \left(\frac{V_{\rm rel}}{5\,{\rm km\,s^{-1}}}\right) \times \left(\frac{M_{\rm BH}}{100\,{\rm M_\odot}}\right)^{-1} \left(\frac{a}{30\,{\rm R_\odot}}\right)^{-1} . \qquad (12)$$

It follows from Eq. (12) that during the several million years of cluster evolution one can expect at least a dozen of close encounters involving binaries with $a \geqslant 30\,\mathrm{R}_\odot$.

4.3 Encounter between a single star and a binary IMBH

Numerical simulations by Gürkan, Fregeau & Rasio (2006) showed that runaway collisions and mergers of massive stars in YMSCs with initial binary fraction larger than $\sim 10\%$ could result in the origin of two VMSs. The subsequent supernova explosions of these VMSs produce two IMBH, which ultimately exchange into a binary (Gürkan et al. 2006; cf. Fregeau et al. 2006).

The IMBH binary (IMBHB) gradually hardens due to the interaction with stars in the cluster's core. When the binary separation reduces to $a \lesssim a_\mathrm{h} \simeq G\mu/4\sigma^2$, where $\mu = M_1M_2/(M_1+M_2)$ and M_1 and M_2 are the component masses of the IMBHB ($M_1 > M_2$), most of stars passing in the vicinity ($\sim a$) of the IMBHB are expelled from the core at high velocity. The average ejection speed attained by the escapers is (Yu & Tremaine 2003)

$$\langle V_\infty \rangle \sim \sqrt{\frac{GM_1M_2}{(M_1+M_2)a}}\,; \tag{13}$$

here we take into account the result of three-body scattering experiments by Gualandris et al. (2005), which showed that Yu & Tremaine [2003; see their Eq. (32)] overestimate $\langle V_\infty \rangle$ by a factor of 2. Some escapers, however, can reach much higher velocities. For an IMBHB with mass ratio of ~ 1 the maximum ejection velocity is

$$V_\infty^\mathrm{max} \sim 1.5\,V_\mathrm{bin}\,, \tag{14}$$

where $V_\mathrm{bin} = [G(M_1+M_2)/a]^{1/2}$ is the relative velocity of the binary components if their orbits are circular (Tutukov & Fedorova 2005). It is clear that the smaller a the larger $\langle V_\infty \rangle$ and V_∞^max. There are, however, two constraints on the minimum value of a, which limit the maximum possible ejection velocity.

First, a should be sufficiently large to prevent the tidal breakup of stars passing through the IMBHB, i.e.

$$a \gtrsim 1.2 \left[\left(\frac{M_1}{\mathrm{M}_\odot}\right)^{1/3} + \left(\frac{M_2}{\mathrm{M}_\odot}\right)^{1/3}\right] \left(\frac{m}{\mathrm{M}_\odot}\right)^{11/30} \mathrm{R}_\odot \tag{15}$$

(for the sake of simplicity we assume a circular binary orbit). It follows from Eqs. (13)-(15) that the smaller the mass of the star the larger velocity it, in principle, can attain; note also that inequality (15) set an upper limit on the mass of a main-sequence star that can be ejected by a shrinking IMBHB. For a main-sequence star of mass $m = 8\,\mathrm{M}_\odot$ (the minimum mass of single stars producing neutron stars) and assuming that $M_1 = 300\,\mathrm{M}_\odot$ and $M_2 = 200\,\mathrm{M}_\odot$, one has from Eqs. (15), (13) and (14) that $a \gtrsim 30\,\mathrm{R}_\odot$, $\langle V_\infty \rangle \sim 800\,\mathrm{km\,s^{-1}}$ and

$$V_\infty^\mathrm{max} \simeq 2\,670\,\mathrm{km\,s^{-1}} \left(\frac{\nu}{0.6}\right)^{-1/2} \left(\frac{M_1}{300\,\mathrm{M}_\odot}\right)^{1/2} \times \left(\frac{a}{30\,\mathrm{R}_\odot}\right)^{-1/2}, \tag{16}$$

where $\nu = M_1/(M_1+M_2)$.

The maximum ejection velocity could be somewhat higher if one consider encounters involving massive post-main-sequence stars, either a blue supergiant or a bare helium core. In this case a massive star can approach the IMBHB much closer than a main-sequence star. Although the blue supergiant star will lose its hydrogen envelope due to the tidal stripping, its helium core can pass within several $\mathrm{R}_\odot$ from one of the binary components without being disintegrated by the tidal force. To estimate the maximum possible velocity attained by the helium core one should consider the second constraint on the binary separation. It follows from the requirement that the gravitational radiation timescale of the shrinking IMBHB (Peter 1964),

$$t_\mathrm{GWR} \simeq 4\times 10^6\,\mathrm{yr} \left(\frac{\nu}{0.6}\right) \left(\frac{M_1}{300\,\mathrm{M}_\odot}\right)^{-2} \times \left(\frac{M_2}{200\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{a}{30\,\mathrm{R}_\odot}\right)^{4}, \tag{17}$$

should be larger than the mean collision time,

$$t_\mathrm{coll} \sim 4\times 10^4\,\mathrm{yr} \left(\frac{n}{10^7\,\mathrm{pc^{-3}}}\right)^{-1} \left(\frac{V_\mathrm{rel}}{5\,\mathrm{km\,s^{-1}}}\right) \times \left(\frac{M_1+M_2}{500\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{a}{30\,\mathrm{R}_\odot}\right)^{-1}, \tag{18}$$

that is $a \gtrsim 12\,\mathrm{R}_\odot$. From Eq. (16) one has that a helium core passing through the IMBHB just before the latter merges due to the gravitational emission can attain a speed as large as $\sim 4\,200\,\mathrm{km\,s^{-1}}$.

5 N-BODY SIMULATIONS OF HYPERVELOCITY STARS

In this section we perform numerical simulations of three-body scatterings with IMBHs, both single and in binaries, in order to obtain the velocity distributions for the ejected stars for the mechanisms described in Sects. 4.2 and 4.3. The simulations are carried out using the `sigma3` package, which is part of the STARLAB[4] software environment (McMillan & Hut 1996; Portegies Zwart et al. 2001a). For a detailed description of the setup of the scattering experiments, see Gualandris et al. (2005).

5.1 Exchange encounters between binary stars and an IMBH

First we focus on interactions in which a binary consisting of two $8\,\mathrm{M}_\odot$ main-sequence stars [with radii of $3.5\,\mathrm{R}_\odot$, see Eq. (3)] encounters a single IMBH of mass in the range $100-1\,000\,\mathrm{M}_\odot$. The relative velocity at infinity between the IMBH and the centre of mass of the binary is set to $5\,\mathrm{km\,s^{-1}}$, in accordance with typical dispersion velocities in YMSCs. The semi-major axis is $a = 0.1\,\mathrm{AU}$, to represent the case of the tighest binaries. In Fig. 1 we present the probability of different outcomes (branching ratios) as a function of the IMBH mass M_BH. For each value of the IMBH mass we perform a total of $2\,000$ scattering experiments, which result either in a fly-by, an exchange or a merger. Ionizations

[4] `http://www.manybody.org/manybody/starlab.html`

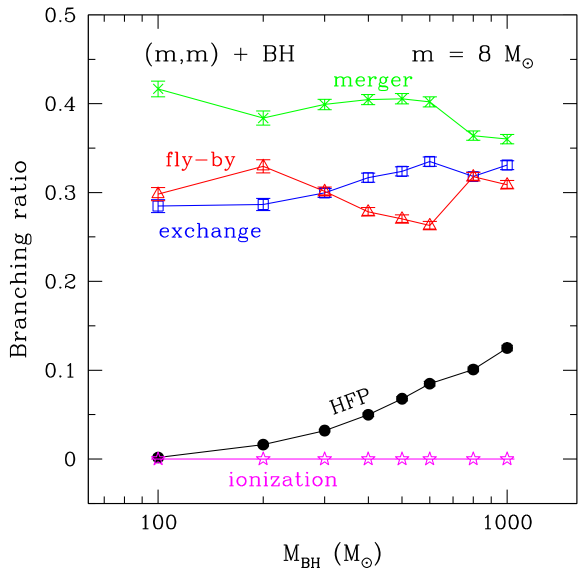

Figure 1. Branching ratio for the outcome of encounters between a binary star and a single IMBH as a function of the IMBH mass. The two binary components are assumed to be $8\,M_\odot$ main-sequence stars and the semi-major axis is $a = 0.1$ AU. The different outcomes are: merger (crosses), fly-bys (triangles), ionization (stars), exchange (squares) and exchange with a high velocity escaper ($V_\infty \geqslant 700\,\mathrm{km\,s^{-1}}$) (bullets). The error bars represent the formal (1σ) Poissonian uncertainty of the measurement.

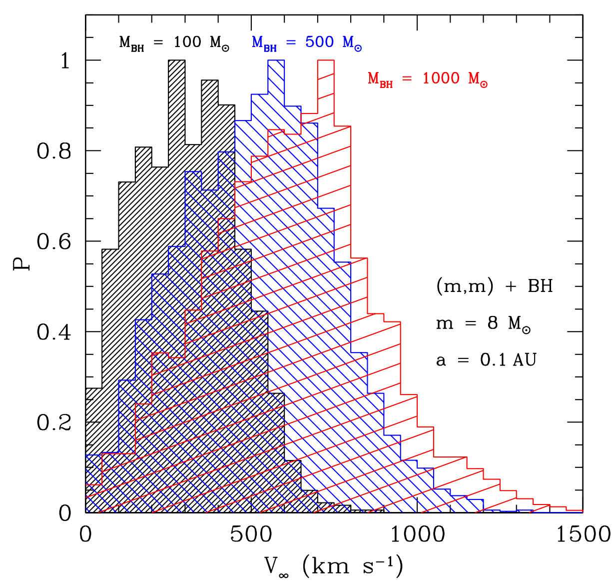

Figure 2. Velocity distributions at infinity for escaping stars in encounters between an equal mass ($m = 8\,M_\odot$) binary star and a single IMBH for different values of the IMBH mass: $M_{\rm BH} = 100\,M_\odot$ (left), $500\,M_\odot$ (middle), $1\,000\,M_\odot$ (right). The binary semi-major axis is $a = 0.1$ AU.

never take place as the binary is too hard to be dissociated by the IMBH (Heggie 1975). Mergers occur in a large fraction (∼40%) of encounters due to the small orbital period of the binary star and mostly involve collisions between the binary components caused by perturbations from the IMBH. Exchange interactions occur in about 30% of encounters, with a probability increasing with the IMBH mass. Since the binary components have equal masses, the probability of ejection for the two stars is equal in exchange encounters. During such encounters, one of the main-sequence stars is captured by the IMBH while the other star is ejected, possibly with high velocity. These encounters are the relevant ones for the production of hypervelocity stars. If the velocity of the ejected star exceeds $700\,\mathrm{km\,s^{-1}}$, we regard the star as a possible progenitor of a hyperfast neutron star (indicated with HFP in the figure). The figure shows that more massive IMBHs are more likely to eject stars with hypervelocities.

The distributions of velocities at infinity for the escaping stars are shown in Fig. 2 for three different values of the IMBH mass: $M_{\rm BH} = 100\,M_\odot, 500\,M_\odot$ and $1\,000\,M_\odot$. In order to obtain stars with velocities $V_\infty \gtrsim 700\,\mathrm{km\,s^{-1}}$, an IMBH more massive than a few hundred solar masses is required. In the case of a $500\,M_\odot$ IMBH, about 20% of all exchanges result in an escape velocity $\geqslant 700\,\mathrm{km\,s^{-1}}$. The fraction increases to 40% for the $1\,000\,M_\odot$ IMBH. We note that even an IMBH of mass $M_{\rm BH} = 100\,M_\odot$ can occasionally (in about 1% of all exchanges) produce an escape velocity $\geqslant 700\,\mathrm{km\,s^{-1}}$.

In order to derive the probability of obtaining the largest possible recoil velocities (see Sect. 4.2), we perform additional scattering experiments with the following parameters: $m_1 = 40\,M_\odot$, $m_2 = 8\,M_\odot$ and $a = 0.15$ AU. The velocity distributions for escapers are shown in Fig. 3 for three different values of the IMBH mass: $M_{\rm BH} = 100\,M_\odot, 500\,M_\odot$ and $1\,000\,M_\odot$. The maximum velocity obtained for each set of parameters is consistent with the predictions derived in Sect. 4.2. The fraction of encounters resulting in velocities larger than $700\,\mathrm{km\,s^{-1}}$ increases from about 7% for $M_{\rm BH} = 100\,M_\odot$ to about 70% for $M_{\rm BH} = 1\,000\,M_\odot$.

The average velocity of escapers scales as $a^{-1/2}$, as can be seen in Fig. 4 and as is expected from Eq.(10). The figure shows the average recoil velocity of escapers (solid symbols) as a function of the initial binary semi-major axis for three different values of the IMBH mass $M_{\rm BH} = 100\,M_\odot, 500\,M_\odot$ and $1\,000\,M_\odot$. The empty symbols indicate the velocity $V_{\rm max}$ for which 1% of the encounters have $V_\infty > V_{\rm max}$. The average and the maximum velocities increase with the mass of the IMBH, as expected from energetic arguments.

In our systematic study of the effect of the initial semi-major axis of the interacting binary we performed further scattering experiments adopting a homogeneous sampling in $\log a$. If the distribution of orbital separations in a star cluster is flat in $\log a$, like in the case of young star clusters (Kouwenhoven et al. 2005), we can superpose the results of these experiments in order to obtain the total velocity distributions of escapers. The resulting distributions for three different values of the IMBH mass are presented in Fig. 5. The average and the maximum recoil velocities increase with the IMBH mass, as in previous cases. The distributions appear much broader than those in Fig. 3, as a result of the sampling in the semi-major axis.

In order to validate the theoretical predictions in Sect. 4.2, we simulated encounters between an IMBH and binaries consisting of a main-sequence star and a He core. We considered main-sequence stars of mass $m_1 = 40\,M_\odot$ and

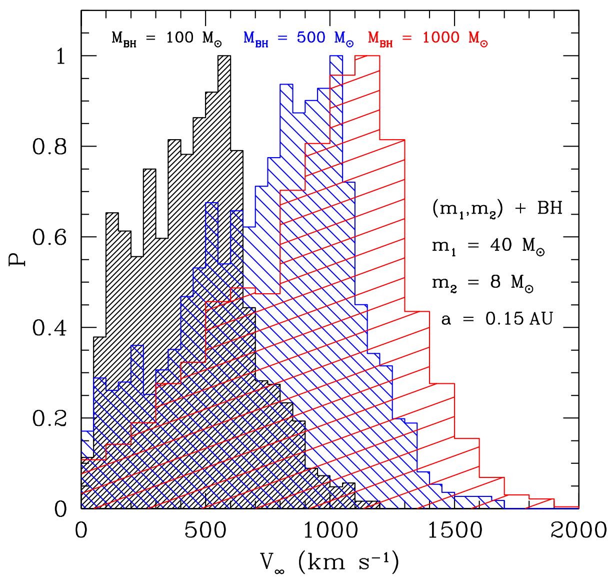

Figure 3. Velocity distributions at infinity for escaping stars in encounters between a binary consisting of a primary star with mass $m_1 = 40\,\mathrm{M}_\odot$ and a secondary star with mass $m_2 = 8\,\mathrm{M}_\odot$, and a single IMBH of mass $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (left), $500\,\mathrm{M}_\odot$ (middle), $1\,000\,\mathrm{M}_\odot$ (right). For this case of unequal mass binaries, we consider as escapers only the least massive stars (m_2). The binary semi-major axis is $a = 0.15\,\mathrm{AU}$.

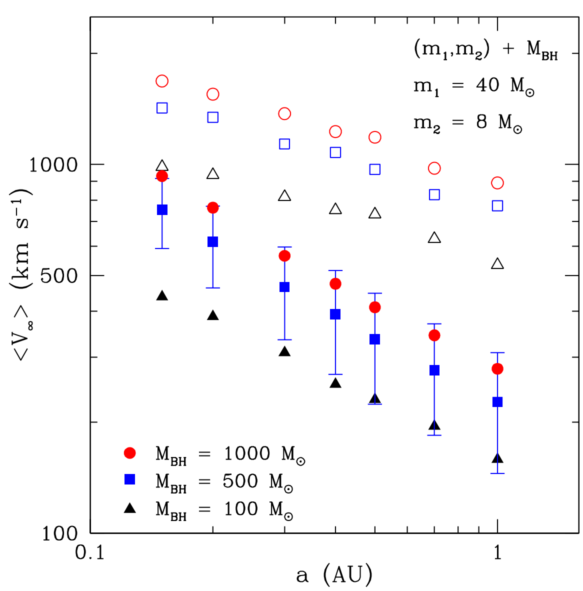

Figure 4. Average recoil velocity of escapers as a function of the initial binary semi-major axis in the interaction of a binary star with IMBHs of different mass: $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (triangles), $M_{\rm BH} = 500\,\mathrm{M}_\odot$ (squares), $M_{\rm BH} = 1\,000\,\mathrm{M}_\odot$ (circles). Solid symbols represent the average velocity obtained from a set of 2000 scattering experimens while the empty symbols indicate the velocity $V_{\rm max}$ for which 1% of the encounters have $V_\infty > V_{\rm max}$. The error bars indicate the 1σ deviation from the mean. For clarity, we only show them for one data set.

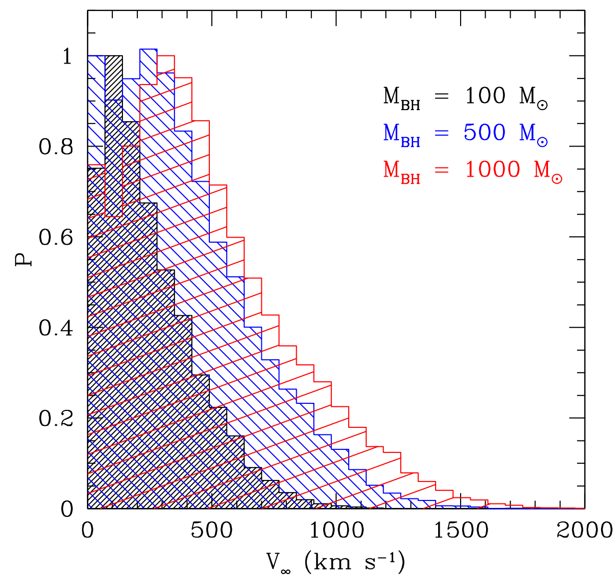

Figure 5. Velocity distributions at infinity for ejected stars after an interaction between a $(40, 8)\,\mathrm{M}_\odot$ binary and an IMBH of mass $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (left), $500\,\mathrm{M}_\odot$ (middle) and $1\,000\,\mathrm{M}_\odot$ (right). These velocity distributions are integrated over the entire range of orbital separations for the initial binary. Only secondary stars ($m_2 = 8\,\mathrm{M}_\odot$) are considered as escapers in this figure.

radius $r_1 = 11\,\mathrm{R}_\odot$ and He cores of mass $m_2 = 5\,\mathrm{M}_\odot$ and radius $r_2 = 0.6\,\mathrm{R}_\odot$ [see Eq. (4)] in binaries of semi-major axis in the range $0.15 - 1.0\,\mathrm{AU}$. Fig. 6 shows the average recoil velocity of escapers (solid symbols) as a function of the initial binary semi-major axis for three different values of the IMBH mass $M_{\rm BH} = 100\,\mathrm{M}_\odot, 500\,\mathrm{M}_\odot$, and $1\,000\,\mathrm{M}_\odot$. The empty symbols indicate the velocity $V_{\rm max}$ for which 1% of the encounters have $V_\infty > V_{\rm max}$. As in the case of encounters between binary stars and a single IMBH, the average and the maximum velocities increase with the mass of the IMBH. Maximum velocities are somewhat higher compared to the case of two main-sequence stars (see Fig. 4). This is due to the fact that, for a fixed initial semi-major axis, a He star can get much closer to a BH than a main-sequence star. The fraction of very close encounters, however, is small and the average velocity of escapers is not substantially higher than in the case of main-sequence binaries.

5.2 Encounter between a single star and an IMBHB

Another exciting possibility, discussed in Sect. 4.3, is mediated by an encounter between a single star and an IMBHB. We simulate these encounters by considering a single star with a mass of $8\,\mathrm{M}_\odot$ and a radius of $3.5\,\mathrm{R}_\odot$ and binary components with masses in the range $100 - 1\,000\,\mathrm{M}_\odot$, both in equal and unequal mass binaries. The semi-major axis is fixed to $a = 30\,\mathrm{R}_\odot \sim 0.14\,\mathrm{AU}$ in all cases and the relative velocity at infinity between the single star and the centre of mass of the IMBHB is set to $5\,\mathrm{km\,s^{-1}}$, as in the previous case. We perform 5 000 scattering experiments for each set of parameters. Except for a few mergers (about 1-2% of all cases), the vast majority of the encounters result

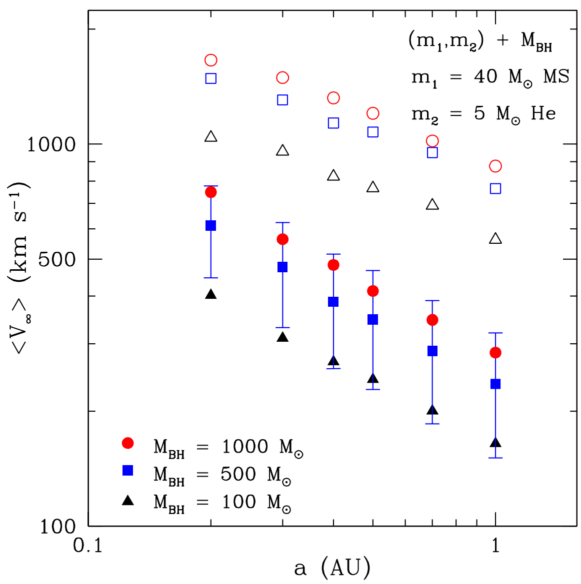

Figure 6. Average recoil velocity of escapers as a function of the initial binary semi-major axis in the interaction between a binary consisting of a main sequence star with mass $m_1 = 40\,\mathrm{M}_\odot$ and a He core with mass $m_2 = 5\,\mathrm{M}_\odot$, and a single IMBH of mass $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (triangles), $500\,\mathrm{M}_\odot$ (squares), $1\,000\,\mathrm{M}_\odot$ (circles). We consider as escapers only the least massive stars, i.e. the He cores. Solid symbols represent the average velocity obtained from a set of 2 000 scattering experimens while the empty symbols indicate the velocity $V_{\rm max}$ for which 1% of the encounters have $V_\infty > V_{\rm max}$. The error bars indicate the 1σ deviation from the mean. For clarity, we only show them for one data set.

in a fly-by. With the random choice of impact parameter adopted in the code (see McMillan & Hut 1996; Portegies Zwart 2001a), typical recoil velocities in such large-distance encounters are modest. The distribution of recoil velocities is strongly peaked at small velocities ($V_\infty < 100\,\mathrm{km\,s^{-1}}$) but shows a long tail towards large velocities ($V_\infty > 700\,\mathrm{km\,s^{-1}}$). The ejection velocities of escapers depend sensitively on how close the single star approaches the IMBHB during the encounter. High velocity ejections are realized only if the star approaches the binary within a distance comparable to the binary separation. The maximum ejection velocity for this scenario is achieved when the incoming star passes through the binary system, very close to one of the BHs. The distance of closest approach is limited only by the tidal radius in the gravitational field of the black hole, which is roughly given by $r_t = (M_{\rm BH}/m)^{1/3} r_*$, where r_* represents the radius of the star. The fraction of encounters resulting in velocities larger than $700\,\mathrm{km\,s^{-1}}$ increases from about 8% for BHs of $100\,\mathrm{M}_\odot$ to 20% for BHs of $500\,\mathrm{M}_\odot$.

In order to prove the critical dependance of the ejection velocity at infinity of escapers on the distance of closest approach to the IMBHB, we perform another set of simulations with zero impact parameter. The values of the BH masses adopted in each set of simulations are reported in Table 1, followed by the average velocity at infinity for escapers, the velocity $V_{\rm max}$ for which 1% of the encounters have $V_\infty > V_{\rm max}$ and the percentage of encounters for which the escapers achieve a recoil velocity larger than $700\,\mathrm{km\,s^{-1}}$

Table 1. List of BH masses adopted in the scattering experiments with zero impact parameter, followed by the average velocity at infinity for escapers, the velocity $V_{\rm max}$ for which 1% of the encounters have $V_\infty > V_{\rm max}$ and the percentage of encounters for which the escapers achieve a recoil velocity larger than $700\,\mathrm{km\,s^{-1}}$. The maximum velocities should be considered as lower limits, as the actual value depends on the random sampling of the initial conditions in the scattering experiments.

M_1 ($\mathrm{M}_\odot$)	M_2 ($\mathrm{M}_\odot$)	$\langle V_\infty \rangle$ ($\mathrm{km\,s^{-1}}$)	$V_{\rm max}(1\%)$ ($\mathrm{km\,s^{-1}}$)	# (%)
100	100	820	2175	53
200	100	950	2380	66
200	200	1130	3070	75
300	200	1260	3230	80
300	300	1430	3875	83
500	300	1610	4170	87
500	500	1845	4800	91
600	500	1915	5025	91
600	600	2050	5175	92
700	700	2185	5595	93
800	700	2270	5740	93
1000	800	2465	6570	95
1000	900	2535	6480	95
1000	1000	2600	6375	96

computed over 5 000 scattering experiments for each set of parameters. The results shown in Table 1 show that very large velocities can be achieved in close encounters between a single star and a massive BH binary. Encounters with impact parameters close to zero are, nonetheless, very rare and we conclude that interactions between a stellar binary and a single massive BH are more likely to result in the ejection of an hypervelocity star.

6 DISCUSSION

In Sect. 4 and Sect. 5 we estimated the maximum possible velocities attained by stars in the course of strong three and four body encounters in the cores of YMSCs and found that these velocities are comparable with or larger than those measured for hypervelocity stars. We therefore suggest that the origin of hypervelocity stars (including the progenitors of hyperfast neutron stars) could be associated not only with encounters involving the supermassive BH in the Galactic centre (Hills 1988; Yu & Tremaine 2003) but also with dynamical processes in the cores of YMSCs, located either in the Galactic disk or near the Galactic centre (e.g. the well-known clusters Arches and Quintuplet). Like in the Galactic disk (see Sect. 3), many YMSCs in the Galactic centre could still be hidden from observers by thick layers of the dust. Theoretical models of evolution and observability of star clusters suggest that the region within 200 pc of the Galactic centre could harbour as much as 50 YMSCs (Portegies Zwart et al. 2001b, 2002). An obvious consequence of our suggestion is that the cores of YMSCs can produce low-mass (i.e. late B-type) stars moving with moderate velocities of $\sim 300-500\,\mathrm{km\,s^{-1}}$ (see Figs. 3 and 5); these stars would contribute to the bound population of the halo stars (see Brown et al. 2007).

It is clear that the hypervelocity stars could also originate in other star-forming galaxies. For example, the position in the sky of the hypervelocity star HE 0437−5439 suggests that it was rather ejected from the Large Magellanic Cloud (LMC) than from our Galaxy (Edelmann et al. 2005). Edelmann et al. pointed out that "if an origin in the LMC can be confirmed, it would allow us to prove either that the LMC contains a–so far undetected–very massive black hole or that other mechanisms are capable of producing hypervelocity stars as well". The results of Sect. 4 and Sect. 5 support the second possibility. Recently, Gualandris & Portegies Zwart (2007) investigated the scenario of the interaction of a binary star with an IMBH in a young star cluster in the LMC and found that an IMBH more massive than $\sim 1\,000\,\mathrm{M}_\odot$ is required to explain the large velocity of HE 0437−5439.

Other possible sites where three and four body encounters (considered in Sect. 4 and Sect. 5) could produce hypervelocity escapers are the dense cores of globular clusters. For example, the exchange interactions involving a binary millisecond pulsar and a BH (either of intermediate or stellar mass) provide a natural channel for production of solitary millisecond pulsars, whose velocities, in principle, can reach ultrarelativistic values. We expect, therefore, that the average peculiar velocity of solitary millisecond pulsars could be larger than that of binary ones (cf. Lommen et al. 2006).

The results of Sect. 4 and Sect. 5 show that massive main-sequence stars hardly can be ejected from YMSCs with a peculiar velocity larger than $\sim 1\,000 - 1\,400\,\mathrm{km\,s^{-1}}$ (unless the IMBH is more massive than $\sim 1\,000\,\mathrm{M}_\odot$) and suggest that the more effective channel for production of hyperfast neutron stars is through the ejection of the helium cores of massive stars; in this case the peculiar velocities of neutron stars could be as large as several thousands $\mathrm{km\,s^{-1}}$. On the other hand, the dynamical processes in the cores of YMSCs can easily produce stars moving with velocities of $\sim 200 - 400\,\mathrm{km\,s^{-1}}$ (typical of pulsars; e.g. Hobbs et al. 2005) and therefore can contibute to the origin of pulsar velocities on equal terms with asymmetric supernova explosions and disruption of binaries following (symmetric) supernova explosions. We do not, however, estimate the production rates of hyperfast neutron stars ejected from YMSCs due to the numerous uncertainties in the fundamental parameters of the clusters and the binaries, like the stellar density in the cluster core, the mass function, the binary fraction, the binary semi-major axis distribution and the binary mass ratio.

The short lifetimes of helium cores ($< 10^6$ yr) imply that their new-born descendants, the (hyperfast) neutron stars, should be located not far ($\lesssim 1$ kpc) from their parent clusters. The separation of PSR B1508+55 from the Galactic plane of ~ 2.5 kpc suggests that it could be the remnant of supernova explosion of a hypervelocity helium core. If the explosion that created PSR B1508+55 was asymmetric than the direction of the pulsar proper motion should not point back to the parent YMSC. The larger the kick the larger the deviation of the pulsar trajectory from the trajectory of the progenitor star. For a natal kick of several hundred $\mathrm{km\,s^{-1}}$, the current orientation of the proper motion of PSR B1508+55 could be consistent with the origin of its progenitor star in the Cyg OB2 association (a young stellar system of mass $\sim 10^5\,\mathrm{M}_\odot$; Knödlseder 2000). Hypervelocity main-sequence stars of mass $\gtrsim 8\,\mathrm{M}_\odot$ ejected at large angles to the Galactic plane end their lives at distances > 10 kpc and thereby contribute to a population of halo and intergalactic supernovae.

The supernova explosion of a high-velocity star occurs within a bow shock-like structure arising due to the interaction of the (post-main-sequence) stellar wind with the ambient interstellar medium. Soon after the supernova explosion the blast wave overtakes this circumstellar structure and starts to interact directly with the unperturbed interstellar medium, so that the supernova blast centre coincides with the geometric centre of the resulting SNR (e.g. Brighenti & D'Ercole 1994). The central location of RX J0822−4300 in the associated SNR Puppis A is consistent with a possibility that both objects are the remnants of a runaway star, which exploded within the bow shock-like structure. An additional support to this possibility comes from the existence of a fan of oxygen-rich knots, moving in the opposite side with respect to the proper motion of RX J0822-4300 (Winkler & Petre 2006), whose origin could be caused by the density asymmetry inherent to the bow shock-like structure. Note that in the case of a slowly-moving massive star the supernova explosion occurs within the wind bubble and the supernova blast centre could be significantly offset from the geometric centre of the SNR (e.g. Gvaramadze 2002; Bock & Gvaramadze 2002). Perhaps this situation takes place in the case of the pulsar PSR B0538+2814 associated with the SNR S 147. The spin-down characteristics of this pulsar (typical of ordinary, i.e. non-recycled, pulsars) imply that its high ($\sim 400\,\mathrm{km\,s^{-1}}$; Ng et al. 2007) peculiar velocity cannot be caused by the disruption of a tight binary system following (symmetric) supernova explosion, while the structure of the associated SNR strongly suggests that the supernova exploded within a pre-existing wind bubble (Gvaramadze 2006). From this follows that the supernova progenitor was a low-velocity star and that the pulsar attained its peculiar velocity due to a natal kick or a post-natal acceleration.

The proper motion vectors of several pulsars located in the high-pressure interiors of their associated SNRs show a trend (Ng & Romani 2004) toward alignment with the pulsar rotation axes (inferred from the symmetry of toroidal nebulae surrounding the pulsars). This trend could be understand if pulsars receive at birth a kick directed along their rotation axes. The observed alignment, however, is not perfect. It is clearly pronounced only for the Vela pulsar[5]. A natural explanation of the misalignment (if one adopts that *all* neutron stars are kicked along their rotation axes) is that the supernova progenitor star had an arbitrarily oriented peculiar velocity, comparable with or larger than the kick velocity received by its descendant at birth. One possibility is that the supernova progenitor was a member of a binary system and that the pulsar peculiar velocity is in part due to the recoil received by the system after the first supernova explosion. Another possibility is that the progenitor star was ejected from the parent YMSC due to the processes discussed in Sect. 4. Thus the hyperfast pulsars produced by supernova explosion of hypervelocity stars should not show any alignment between their spin axes and proper

[5] For an alternative explanation of this alignment see Radhakrishnan & Deshpande (2001) and Deshpande & Radhakrishnan (2006).

motion vectors. This inference, however, would be difficult to prove since the hyperfast pulsars rapidly (on a time-scale of $\sim 1.4\times 10^4 \, v_{1\,000}^{-5/3}(E_{51}/n_{\rm ISM})^{1/3}$ yr, where $v_{1\,000}$ is the pulsar peculiar velocity in units of $1\,000\,{\rm km\,s^{-1}}$, E_{51} is the supernova energy in units of 10^{51} erg, and $n_{\rm ISM}$ is the number density of the ambient interstellar medium) leave the confines of their parent SNRs. The only known hyperfast NS associated with a SNR (RX J0822−4300 in Puppis A; Hui & Werner 2006; Winkler & Petre 2006) is a radio-quiet object (Gaensler, Bock & Stappers 2000), that makes impossible to infer the direction of its rotation axis. One can also infer the orientation of the pulsar rotation axis using the radio polarization measurements (e.g. Deshpande, Ramachandran & Radhakrishnan 1999; Johnston et al. 2005). As expected, the proper motion of the hyperfast pulsar PSR B1508+55 shows a large misalignment of $\sim 71^{\circ}$ (or $\sim 19^{\circ}$, depending on whether or not the linear polarization of the pulsar radio emission is parallel or orthogonal to magnetic field; see Chatterjee et al. 2005).

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